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# Spectral Analysis of RXTE Observations of A3667

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## ABSTRACT

X-ray emission from the cluster of galaxies A3667 was measured by the PCA and HEXTE experiments aboard the RXTE satellite during the period December 2001 - July 2002. Analysis of the  $\sim 141$  ks RXTE observation and lower energy ASCA/GIS data, yields only marginal evidence for a secondary power-law emission component in the spectrum. The 90% confidence upper limit on nonthermal emission in the 15-35 keV band is determined to be  $2.6 \times 10^{-12}$  erg-cm<sup>-2</sup> s<sup>-1</sup>. When combined with the measured radio flux and spectral index of the dominant region of extended radio emission, this upper limit implies a lower limit of  $\sim 0.4 \mu$  G on the mean, volume-averaged, intracluster magnetic field in A3667.

*Subject headings:* Galaxies: clusters: general — galaxies: clusters: individual (A2256) — galaxies: magnetic fields — radiation mechanisms: non-thermal

## 1. Introduction

The spectral and spatial resolutions of current X-ray satellites allow a more realistic description of gas properties and a search for new phenomena in clusters of galaxies. Spectral diagnostics alone can reveal the presence of a second spectral component that may indicate either a more complex temperature distribution than a simple isothermal (with its associated primary thermal emission), or an appreciable energetic electron population that radiates non-thermally. Clearly determining that the gas is non-isothermal is important for a more precise description of IC gas properties, evolution, and for estimation of the cluster total mass, as well as for our ability to use the gas as a more precise cosmological probe. The detection of an appreciable level of non-thermal (NT) emission in clusters with measured extended regions of radio emission (*e.g.*, Rephaeli 1977, 1979) is also very important as an essential second observable which is needed in order to determine the strength of magnetic fields, and for estimating densities and energy content of relativistic electrons (and protons).

While considerable work is being done to investigate the temperature structure of intracluster gas, relatively few searches for non-thermal (NT) emission were carried out. These began with archival analysis of HEAO-1 data (Rephaeli, Gruber & Rothschild 1987, Rephaeli & Gruber 1988), and continued with CGRO (Rephaeli, Ulmer & Gruber 1994) and ASCA (Henriksen 1999) observations, yielding only upper limits on spectral power-law components. The improved sensitivity and wide spectral band of the RXTE and BeppoSAX allowed a more detailed spectral analysis of long exposure measurements that resulted in significant evidence for NT emission in Coma

(Rephaeli, Gruber & Blanco 1999, Fusco-Femiano *et al.* 1999, Rephaeli & Gruber 2002), A2256 (Fusco-Femiano *et al.* 2000, Rephaeli & Gruber 2003), A2319 (Gruber & Rephaeli 2002), A119 & A754 (Fusco-Femiano *et al.* 2003a), and in the moderately distant cluster RXJ0658-5557 (Petrosian 2003). However, the claimed NT emission in A754 could possibly be from a radio galaxy (Henriksen, Hudson & Tittley 2003).

Results of two different analyses of a second BeppoSAX observation of Coma were reported very recently: According to Rossetti & Molendi (2003), the full PDS dataset (with a total on-source exposure of  $\sim 166$  ks) no longer shows significant evidence for a NT component, a claim that is disputed by Fusco-Femiano *et al.* (2003b). Analysis of the same data by the latter authors yields a very significant NT component at a level that is only slightly lower than originally reported by Fusco-Femiano *et al.* (1999).

Since NT electron populations have a wide energy range, their emission could possibly be detected also in the EUV range. It has been claimed that low energy emission observed in a few clusters by ROSAT and, in particular, by the EUVE (in the 65 – 245 eV band), is in excess of what is predicted from thermal emission by IC gas, and that the excess emission is NT (*e.g.*, Lieu *et al.* 1996, Sarazin & Lieu 1998, Bowyer *et al.* 1999, 2003). Due to the very limited spectral range of the EUVE measurements this identification is uncertain. Analysis of line and continuum XMM measurements of soft emission from a sample of clusters seems to suggest that the excess emission is thermal emission from warm gas (Kaastra *et al.* 2003).

The number of clusters observed at high ( $> 30$  keV) energies is only a small fraction

of the  $\sim 40$  clusters in which extended radio emission has already been measured. It is of considerable interest to enlarge the small sample in order to begin a more systematic study of NT phenomena in clusters. Here we report the results of an analysis of  $\sim 141$  ks RXTE observation of the ‘merging’ cluster A3667.

## 2. Observations and Spectral Analysis

A3667, a rich southern cluster at  $z = 0.055$ , has a bimodal galaxy distribution, large velocity dispersion, distorted X-ray morphology, and complex extended regions of radio emission (*e.g.*, Rottgering *et al.* 1997). These features are thought to indicate that the cluster is undergoing strong merging activity. Of particular relevance is the very large, elongated and off-center region of radio emission. The spectrum of this dominant source (point sources are estimated to contribute only a few percent of the total emission) can be described in terms of an overall, single value of the spectral (energy) index,  $\alpha \sim 1.1$ , in the frequency range  $\sim 0.4 - 2.3$  GHz, and a flux of  $5.5 \pm 0.5$  Jy at 843 MHz (Rottgering *et al.* 1997).

Analysis of ASCA observations of A3667 yielded a mean gas temperature of  $7.0 \pm 0.6$  keV over a large region with  $\sim 22'$  radial extent (Markevitch *et al.* 1999). More recently *Chandra* measurements have led to a more detailed temperature and brightness structure in the central region showing evidence for large temperature gradients, including a region where the gas temperature is  $\sim 11$  keV, possibly due heating of the gas merger shocks (Vikhlinin *et al.* 2001).

A3667 was observed with RXTE for  $\sim 167$  ks during the period December 2001 - July 2002. The application of data selection criteria recommended by the RXTE project re-

sults in 141 ks of screened PCA data, spaced irregularly over the observing period. These were collected in two of the 5 detectors. For the HEXTE, which beam-switches observations with 32-second dwells between source and background fields, and has in addition about 50% detector dead time, the net observation time was 54.6 ks with each of the two clusters. A systematic error of 0.8% per energy channel was added in quadrature to the statistical error of the PCA data; no systematic error was used with HEXTE data. On time scales of two weeks or longer, the limit to variability observed with PCA was less than 1%. Because of the much lower signal to background, corresponding HEXTE limits to variability are weaker, about 20%.

To extend the spectral range lower, analysis was conducted jointly with archival ASCA GIS observation (of 1995 April 16) lasting and 39 ks. GIS2 and GIS3 0.8 – 8.0 keV spectra were accumulated in a field with a diameter of 14 arcminutes centered on the cluster, a region that included the great majority of the cluster emission. SIS data for the observation were found unsuitable for analysis because of noise. Systematic errors were not added to the GIS data.

Preliminary spectral analysis on the direct instrument data showed no features which departed on small scales (*i.e.* spectral lines or edges) from the thermal form which clearly dominates the bulk of the observed cluster spectrum. We therefore found it appropriate to combine data in order to make small differences of  $\chi^2$  from model fitting more distinguishable against the statistical noise of the highly oversampled data. As a first step we combined the data from the two PCA detectors and also the data of the two HEXTE clusters. For all three instruments we then

joined the counts in adjacent energy channels into wider energy bins at a density of two to three per detector energy resolution element. Doing so reduced the number of energy bins in the analysis from over one thousand to 60. These channels are displayed in the figure. It should be noted that confidence intervals for parameter estimates, as shown in the Table, depend on differences of  $\chi^2$ , and are only weakly sensitive to choices of binning.

Both the RXTE and ASCA data are collected essentially from the entire cluster, so that the joint fits here need not consider possible spectral differences resulting from gradients in the cluster. To account for possible inter-calibration errors between the instruments, adjustable scaling constants are employed. These are treated as ‘uninteresting’ parameters in the fitting, provided (as is the case here) that they float to values within 5 – 15% of unity, consistent with our experience in analyzing other sources with this combination of instruments.

We have considered three spectral models: thermal emission from isothermal gas (based on a Raymond-Smith emission code), two-temperature thermal, and a thermal plus a power-law model. The hydrogen column was fixed at the Galactic value,  $N_H \simeq 4.7 \times 10^{20} \text{ cm}^{-2}$ . With the lower threshold at 0.8 keV, the GIS data are insensitive to the value of  $N_H$  unless it is much larger. Indeed, if this value is allowed to float in the fits a best-fit is found which is only slightly lower than our assumed value. Using these models, fits to the joint data provide only weak evidence of the need for an extra component beyond isothermal. The  $\chi^2$  of 56.4 (57 degrees of freedom [dof]) for an isothermal fit is acceptable. Inclusion of a second component reduces  $\chi^2$  modestly to 46.6 (55 dof) with an extra 0.9

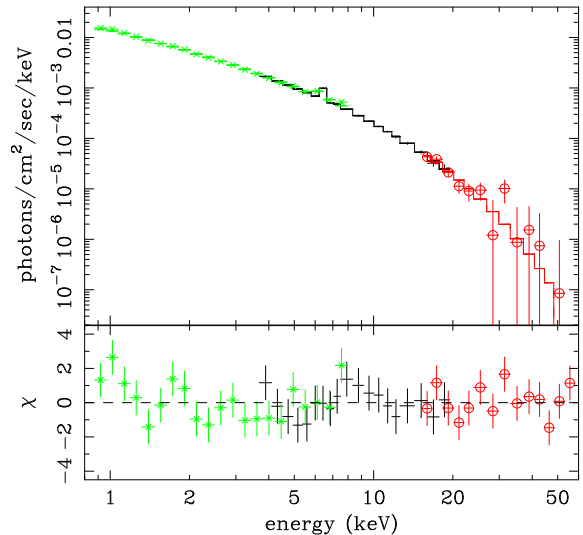


Fig. 1.— RXTE and ASCA/GIS spectrum of the A3667 with folded Raymond-Smith ( $kT \simeq 7.3$ ) model. ASCA/GIS data are shown in (green) asterisks, (black) crosses are PCA data, and HEXTE data points are marked with (red) circles (with 68% error bars). The total fitted spectrum is shown with a histogram, and deviations between the model and data points (normalized to the respective standard error) are shown in the lower panel.

keV thermal component, or to 51.3 (56 dof) with an extra power-law of index 2.1, as determined from the radio spectrum. If the power law index is allowed to vary, its best-fit photon index assumes the rather steep value of 5.0, but it is almost unconstrained. With four “interesting” parameters, – temperature, abundance, and normalization of the thermal component, plus power-law normalization – the change in  $\chi^2$  (Lampton *et al.* 1976) gives 90% error limits for the 2-20 keV power-law flux of  $(0.0 - 8.1) \times 10^{-11} \text{ erg-cm}^{-2} \text{ s}^{-1}$ . The temperature for the main spectral component is in the range  $\sim 7.3 - 7.5 \text{ keV}$  for all three cases, with formal ( $1\sigma$ ) errors of  $\sim 0.1 - 0.3$

keV.

This RXTE observation yields evidence for a second spectral component which is just significant at the 90% confidence level. With the spectral photon index fixed at 2.1, the value predicted from the radio spectrum, the best-fit 2-20 keV flux is  $(4.0 \pm 1.8) \times 10^{-12}$  erg-cm $^{-2}$  s $^{-1}$ . The 90% confidence upper limit on the 15-35 keV flux is  $2.6 \times 10^{-12}$  erg-cm $^{-2}$  s $^{-1}$  (with four relevant parameters). The fraction of the total flux in the best-fit secondary component, whether low-temperature thermal or power-law, is small, of the order of a few percent. We report these values, together with 90% confidence errors, as “secondary flux fraction” in the Table for three interesting energy bands. Nevertheless, given the possible effects of background subtraction and calibration errors, we feel that we cannot claim detection of a second component at 90% confidence, even though this is a formal result of the analysis.

A3667 was observed by BeppoSAX for  $\sim 113$  ks in May 1998 and October 1999. Analysis of the measurements (Fusco-Femiano *et al.* 2001) showed marginal evidence (*formally* significant at the  $\sim 2.6\sigma$  level) for a secondary power-law component, and this only if the gas temperature was fixed at the value (7 keV) determined from previous ASCA measurements. Clearly, the need to *assume* a value for the temperature, rather than determining it in a simultaneous fit to the parameters of both components (a procedure that is difficult to accomplish with BeppoSAX due to the lack of spectral overlap between the PDS and the lower energy MECS experiments), introduced a substantial uncertainty in the deduced significance of any power-law emission. Therefore, only an upper limit on nonthermal emission was reported by Fusco-

Femiano *et al.* (2001); in the 15-35 keV range the flux limit is  $4.2 \times 10^{-12}$  ergs cm $^{-2}$ s $^{-1}$ , moderately higher than our limit in the same energy band.

### 3. Discussion

A3667 is the fourth (following Coma, A2319 & A2256) in a sample of clusters with extended radio emission whose RXTE observations were analyzed by us, and the only one for which we do not find clear evidence for a second spectral component. With no spatial information, the absence of evidence for a secondary thermal emission component does not yield useful information on a large scale temperature gradient. In a cluster with extended radio emission, the main interest in obtaining an upper limit on NT emission stems from the fact that it sets a lower limit on the mean, volume-averaged value of the magnetic field in the central region of the cluster. With the above value of the flux upper limit, and a spectral index of 2.1 inferred from the radio spectrum, we set a lower limit of  $\sim 0.4$   $\mu$ G on the mean value of the magnetic field.

In assessing the meaning of this limit it has to be realized that radio emission in A3667 has a complex morphology, with very different field values in different regions. From a more basic point of view, it should also be remembered that several implicit assumptions are usually made in linking the synchrotron and Compton formulae in order to determine  $B_{rx}$  from radio and X-ray measurements (Rephaeli 1979, Goldshmidt & Rephaeli 1993). These are too often ignored, especially when values of  $B_{rx}$  are contrasted with field values deduced from co-added statistical analysis of Faraday rotation measurements (*e.g.*, Clarke, Kronberg, and Böhringer 2001). The latter method is also prone to substantial in-

Table 1: Results of the spectral analysis

Parameter	Single Thermal	Double Thermal	Thermal + Power-law
$kT_1$ (keV)	$7.3 \pm 0.2$	$7.5^{+0.7}_{-0.3}$	$7.3 \pm 0.2$
$kT_2$ (keV)		$0.9^{+3.7}_{-0.8}$	
Secondary flux fraction			
2-10 keV		$0.003^{+0.155}_{-0.003}$	$0.045^{+0.048}_{-0.045}$
0.8-40 keV		$0.016^{+0.153}_{-0.016}$	$0.052^{+0.056}_{-0.052}$
Abundance (solar)	$0.22 \pm 0.04$	$0.22 \pm 0.05$	$0.24 \pm 0.05$

All quoted errors are at the 90% confidence level.

herent (*e.g.*, Newman, Newman & Rephaeli 2002) and systematic (Rudnick & Blundell 2003, but see Ensslin *et al.* 2003) uncertainties.

Since the number of clusters observed at high X-ray energies is small, the observation of additional clusters (either with or without known extended radio emission) is of obvious interest, even if only an upper limit is obtained on NT emission: While observations of more clusters with extended radio emission are very desirable, observations of other clusters, interesting in their own right, are also useful as a control sample.

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